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Abstract: In this study, the development of a wide-area, multi-objective cost function is explained. The cost function is designed for implementation on wide-area phasor measurement unit data. In this study, the cost function was applied to the IEEE 30 and 57 Bus models for monitoring and control purposes. Although the cost function was originally intended as a situational awareness tool that indicated system health; it has now been applied as a control metric for the operation of on-load tap changing transformers on a variety of standard IEEE test systems. The system benefits, relative to conventional local control, are quantified. The primary metrics for testing protection outcomes are maximum voltage deviation and line thermal overload. The wide-area optimisation is assessed from a voltage profile, reactive power demand, and transmission losses. The benefits of this type of wide-area control are demonstrated in a variety of situations and environments.

1 Introduction

At present, most monitoring and control functions on the power system are performed, directly or indirectly, with supervisory control and data acquisition (SCADA) systems. These assets are usually operated to keep a single local variable within certain bounds; e.g. voltage or frequency. SCADA architecture has been in development for decades but has had its limitations [1], which can include low bandwidth and reporting rates. Unfortunately, low reporting rates can mask transients of protection and control interest.

Phasor measurement units (PMUs) were developed to provide better observability of the power system; the two key advantages were a higher reporting rate and time synchronisation. The increased reporting rate, typically in the region of 10–50 frames per second (on a 50 Hz system), is a step change in resolution. PMU synchronisation allows units at disparate locations to be compared, particularly utilising phase angles. PMUs are primarily used for monitoring purposes, but their potential for control was obvious from the start and contributed to acronyms such as wide-area monitoring for projection and control (WAMPAC) [2], flexible alternating current transmission system (FACTS) [3] and SMART grid [4].

The method presented in this study was developed for a section of the network on the Northern Irish power system, with significant wind resource. Several special protection systems have been installed to protect vulnerable. This region of the network contains controllable assets that can be utilised to protect and optimise the whole region, as described in [5, 6]. A PMU network was planned but unfortunately did not go ahead. The following research is largely intended as a demonstration of the value of WAMPAC.

WAMPAC systems could utilise distributed assets, such as on load tap changing (OLTC) transformers, to optimise and protect the power system. A WAMPAC method was applied to OLTC transformers on the standard IEEE 30 and 57 Bus models. Typically, these transformers operate to reduce local busbar voltage deviation. In this study, the transformers were operated to reduce an optimisation and protection metric (OPM) that was derived from a cost function, like the one described in [5, 6]. Reducing the OPM invariably improved particularly in the protection region.

Wide-area control is a challenge given the many-to-many nature of the problem, that is, data is provided from multiple measurement devices placed across a wide area and this data is used to control multiple assets. This problem was made tractable with the scalar OPM as a middle man. In this study, data from each bus and branch on the IEEE 30 and 57 Bus models were used in the creation of the OPM; this data could be replaced with PMU data or appropriate SCADA data. A gradient descent technique was employed to reduce the OPM to a global minimum using the OLTC transformers.

The IEEE test systems are standard research tools and the Siemens PSS/E models were provided by the Information Trust Institute [7]. The power system models were activated, solved, monitored, adjusted and iterated using a Python script, through the Python PSS/E application program interface [8]. All the logic to generate the OPM, optimise tap settings and output data and metadata was performed in Python.

On the IEEE models, the load was varied between 0 and 250% of standard load, in increments of 0.5%. In this study, wide-area optimisation is compared with conventionally control where control bus voltages are maintained. For each load case, OLTC transformer was adjusted with local or wide-area considerations. After every iteration, a new load flow was calculated. The wide-area optimised model outperformed the locally controlled model in all cases, in both the optimisation and protection environment. The Python code that applied the wide-area optimisation method was implemented on the IEEE 9, 14, 39 and 118 Bus models without modifications and provided consistent performance.

The IEEE 30 Bus model was the only standard IEEE model with thermal ratings. On this model wide-area control succeeded in delaying the onset of thermal and voltage infringements. The IEEE 57 Bus model is prone to intermittent bus voltage infringements on the periphery of the network; this optimisation method is particularly well suited for this type of optimisation and protection problem.

The wide-area optimisation and protection cost function was initially created as a means of assessing system health before it was applied as a control metric. The generation and application of this methodology are intended to demonstrate potential uses of PMU data, including real-time wide-area monitoring, protection, and control. The small size of the scalar OPM value, generated from the cost function, makes it ideal for improved situational awareness and low bandwidth SCADA communications.

Cost functions have been applied to low-voltage networks to realise similar optimisation results, such as in [9, 10]. Commercial products, such as SuperTAPP n+ [11], are also available to extend visibility when operating OLTC transformers. Another type of wide-area control is the angle constraint method which can be used to protect transmission corridors, such as in [12].

2 Use of a cost function

Most control assets can be reduced to a single dimension of control; e.g. an OLTC transformer or a capacitor bank can be adjusted up or down, while a generator could have its real and reactive power adjusted separately. The problem with wide-area control is that a huge number of measurements may be informing the operation of the control asset. This can be considered a dimensional reduction problem as the multiple dimensions/ measurements, from PMUs across a network, need to be reduced to a single dimension for controlling assets.

A multi-objective cost function allows many competing interests to be represented in an equation, the factors of which reflect the weighting given to variations in each parameter. As an example, variation in transmission line voltage is less acceptable than significant voltage variations on the distribution systems. The equations presented in this study can be adjusted by a scaling factor or the values in the tables changed to reflect grid codes.

The cost factors can be differentiated into optimisation cost factors and protection cost factors. The optimisation cost factors tend to favour more efficient operation closer to prescribed limits and are derived from many measurements. The protection cost factors are generated from the bus or branch operating closest to its limit. The protection factors tend not to play a role in the general operation, but quickly dominate as an infringement is approached. The optimisation factors vary smoothly, while step changes are introduced if the voltage or current exceptions occur.

One danger of discontinuities, or steps, in a cost function, is the creation of local minima. Local minima are a problem for gradient descent techniques as a local optimum solution can prevent the discovery of a global optimum. It was discovered that local minima could occur when a small section of the network was investigated, such as in [5], but on the IEEE systems studied no local minima were found.

2.1 Elements of the cost function

2.1.1 Optimisation cost functions: The optimisation functions were used to reduce general bus bar voltage deviation, reactive power flow, and transmission losses. These considerations dominate control operations under normal circumstances. Optimisation considerations were prevented from effecting protection operations by limiting their maximum contribution to the OPM. Each optimisation cost factor has an intended operation range of ±0.5 and an effective constraint of ±1.5. Protection considerations are entirely dominant when any cost factor exceeds 10 and they rise linearly to 100 before step changes of 300+ are introduced. The scale of the values is entirely arbitrary but their relative values, bounds and step changes are based on engineering priorities.

A bus bar voltage deviation made no contribution to the OPM if it was within $98.5\% < V_{\text{Bus}} < 101.5\%$ of nominal (this should be considered when interpreting (1)). Each bus then contributed the square of the deviation from ±0.015 per unit. The scaled (0.2 in (1)) average of the squared deviations was returned as the voltage optimisation cost factor, (1). This function could return a value of 14.45 if all buses had a ΔV_{Bus} of 10%; however, by this stage, the voltage protection function would return a value of 100+. This metric has a value of 3 when the average deviation is 5.4%

$$V_{\text{opt}} = 0.2 \times \frac{\sum_1^N (\Delta V - 1.5)^2_{\text{PU}}}{N}. \tag{1}$$

Typically, it is preferable to source reactive power close to the reactive power demand. It is also preferable to distribute reactive power over high-voltage lines. If a PMU is monitoring a power line the reactive and apparent power flow in that line is easily calculated for insertion into (2). For this cost factor, the reactive power flow on each line was normalised by the apparent power flow and the penalty for each line was given as line resistance divided by voltage squared, as shown in (2). The normalised result is similar to a power factor and varies between 0 and 1; this number is multiplied by three to balance the weightings. This number is dimensionless as it is effectively inverse power multiplied by power

$$Q_{\text{opt}} = 3 \times \frac{\sum_1^N (R_{\text{Line}}/V^2) \times (Q_{n\_\text{Send}} + Q_{n\_\text{Receive}})}{\sum_1^N (R_{\text{Line}}/V^2) \times (S_{n\_\text{Send}} + S_{n\_\text{Receive}})}. \tag{2}$$

The final optimisation cost factor was transmission line losses or power flow optimisation. The fraction of power lost to transmission losses was calculated from the sum of the I^2R line losses divided by the total generation on the system; both of these units are easily obtained from appropriately placed PMUs. Displayed in (3) is the function that transforms the fraction of power lost to transmission loss into the cost factor. The equation displayed causes the cost factor to vary by ∼±1 for ±10% change in transmission losses. Similar to voltage optimisation, this cost factor losses its potency at reduced transmission losses, as can be observed in Table 1. This cost factor returns a significant constant value, which can act as a proxy value for transmission losses, but variation in the cost factor is well bounded

$$I^2R_{\text{opt}} = \log_{1.1}\left(1 + 100 \times \frac{\sum \text{Trans\_Losses}}{\sum \text{Power\_Gen}}\right). \tag{3}$$

2.1.2 Protection cost functions: The two protection cost factors address bus voltage and line current. The determination of protection cost factors was simpler than the method for creating the optimisation functions, as only the bus or line with the greatest infringement is considered. Consequently, the cost factors are more deterministic and many of the scalars and step changes arise from grid codes and engineering considerations.

The combined variation of the optimisation functions should not exceed ±5. The protection regime is entered when a protection cost factor exceeds 10 and increases continuously until an exception occurs. An infringement causes a step change in the cost factor, the magnitude of which is proportional to the severity of the infringement. The step changes provide triage when exceptions are inevitable.

High bus bar voltage infringements can have a negative effect on customers, in terms of quality of service, damage to equipment and increased demand. Low bus bar voltage also has a deleterious effect on a customer's quality of service but more seriously can precipitate voltage collapse on networks. Both conditions are tightly constrained by grid operators and regulators. Rapidly deployable, low-cost PMUs offer the potential of directly monitoring most important substations. Shown in Table 2 is the contribution to the OPM from the highest bus voltage on the system.

Transmission and distribution lines have a maximum current carrying capacity, referred to as their thermal limit. Resistive losses in lines heat the conductors causing them to sag, raising the risk of line to ground short circuits. Frequent expansion and contraction can also place additional stresses on the line, prematurely weakening it. Displayed in Table 3 are the contributions of the line with the heaviest loading would make to the OPM. Exceeding a

Table 1 Variation in transmission optimisation cost factor

Trans. loss, %	I^2R_{opt}	Trans. loss, %	I^2R_{opt}	Difference
10	25.2	9	24.2	1.0
5	18.8	4.5	17.9	0.9
2	11.5	1.8	10.8	0.7
1	7.3	0.9	6.8	0.5

Table 2 Contribution to OPM from voltage protection

Bus voltage deviation	<5%	6%	7%	8%	9%	10%	>10%
V_{prot}	0	1	5	10	30	100	>350

Table 3 Contribution to OPM from thermal protection

Line loading	<85%	90%	95%	100%	>100%
I_{prot}	0	5	15	100	>300

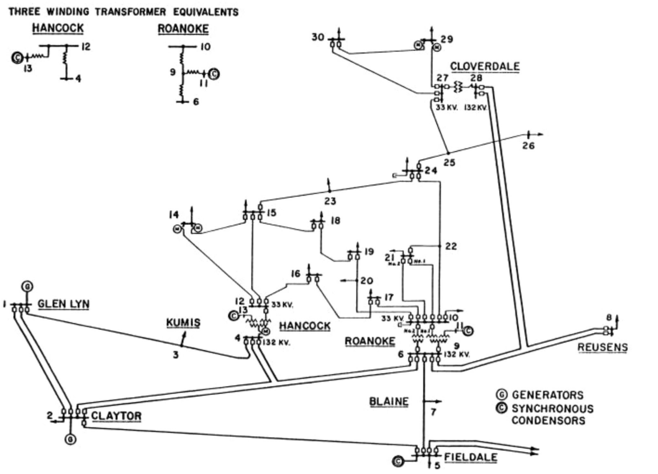

Fig. 1 *Traditional representation of IEEE 30 Bus System [7]*

line's thermal loading, especially for a small encroachment and for a short time, is taken as less severe than a voltage infringement, and this is reflected in the step changes 300 versus 350.

3 Optimisation of IEEE models

The only adjustable assets on the IEEE models were the OLTC transformers and these were operated to reduce the OPM. The same approach was implemented on a model of the Northern Irish power system [5, 6], which contained switched capacitor banks. On this model, the capacitor banks and reactive power delivery of a wind farm were optimised. The real and reactive power dispatch from generators on the IEEE systems could have been optimised. This research is, however, intended to demonstrate FACTS-like operation and as a tool for transmission and distribution system operators. In practice, optimising the OLTC transformers that connect the generators to the power system went some way to controlling generator dispatch.

3.1 Gradient descent method

There are many advantages of working with a simulated power system; one of them is the ability to test a huge number of system configurations without consequences. This approach was applied to tap changer optimisation. On any model, under a given load state, a unique combination of tap changer positions determined the load flow on the model. The model was optimised by adjusting each OLTC transformer up and down a single tap, and the OPM calculated for each new state (this is effectively a partial differentiation method). The state that returned the lowest state was then selected and applied. This process was continued until the starting state is the optimal state. As the load was incremented the previous tap settings were applied and significant system changes only occurred when operating limits encroached.

4 Wide-area control results

The control methods were assessed in terms of their optimisation and protection characteristics. The optimisation characteristics related to mean bus bar voltage deviation, the reactive power demand of the network and total transmission losses. The protection characteristics were investigated in terms of maximum bus bar voltage deviation and maximum line loading.

The OPM can be used as a tool for assessing system health as load and control type vary. This report primarily focuses on the protection outcomes that arose from mitigation of line thermal overload, individual bus bar voltage exceptions, and later voltage collapse. Comment is made in relation to mean bus bar voltage deviation, reactive power flow, and transmission losses.

4.1 IEEE 30 Bus model

The IEEE 30 Bus model is a development of the IEEE 14 Bus model [7] and the optimisation outcomes were similar. The primary difference between the models is the addition of the high-voltage lines that connect buses 6, 28 and 8, Fig. 1. This addition reinforces a remote and vulnerable section of the 14 Bus model. After the improvement, wide-area optimisation of the 30 Bus System was marginally less than that achieved on the 14 Bus System. The comparison of wide-area control on the 14 Bus model, to standard operation of the 30 Bus model, can be informative for studies into deferment of grid reinforcement, a promise of WAMPAC [1].

The potential for wide-area optimisation on this network is somewhat limited by the relatively few control assets (four OLTC transformers) and the limited size of the network. Larger networks (such as the 57 Bus System) can offer greater potential for wide-area optimisation as it effectively utilises FACTS-like operation [3]. Nevertheless, appreciable improvements were made, but these could have been enhanced with direct control of the high-voltage (HV) network.

Displayed in Fig. 2 are the variations in OPM (blue), mean voltage deviation (red) and maximum bus voltage deviation (orange), with system loading. For any given load state, a unique load flow is found, this is largely determined by the tap changer position. In the locally optimised case (dashed lines), OLTC transformers operate to maintain set bus voltage. In the wide-area optimised case, OLTC transformers are operated to lower the OPM. For any unique load and tap setting, a single value for the OPM is returned. The OPM can be used to infer system conditions, where small variations at a low OPM (<20) indicate optimisation considerations, a moderate OPM ($20 < \text{OPM} < 300$) indicates deteriorating conditions, step changes that cause the OPM to exceed 300 indicate system infringements and the last step to >1000 is driven by voltage collapse and unintentionally by the voltage profile metric. The first step change in OPM can be observed in Fig. 2 occurring at a load of 126.5% in the locally optimised case, wide-area optimisation only succeeded in delaying this infringement by 2.5%. The exception occurred on the line connecting Bus 2 to Bus 4 in Fig. 1. The increase in the OPM that begins at a load of 115%, results from the line load exceeding 85%. Wide-area control achieved the mitigation by raising the HV at the expense of lowering distribution voltages. The raised voltages resulted in lower current flow for equal power flow on the HV network.

The second step change in OPM occurred at a load of 144% on the locally optimised model and at a load of 151% on the wide-area optimised model. In this case, the voltage exception occurred at Bus 7, a load bus on the HV system. Despite the limited control over the HV system, wide-area control still had a positive effect in deferring infringements. The positive effects are predicated on the observation of all relevant busses and a flexible control scheme that can identify optimal solutions.

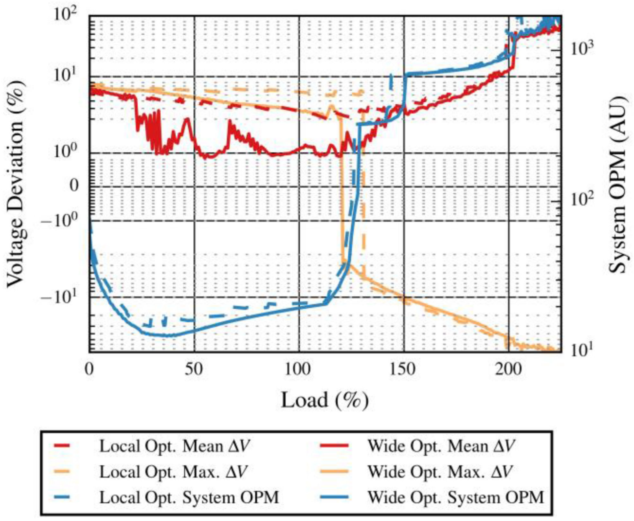

Fig. 2 *Variations in mean and max. voltage deviation, along with OPM. The load is varied under local and wide-area control, IEEE 30 Bus System*

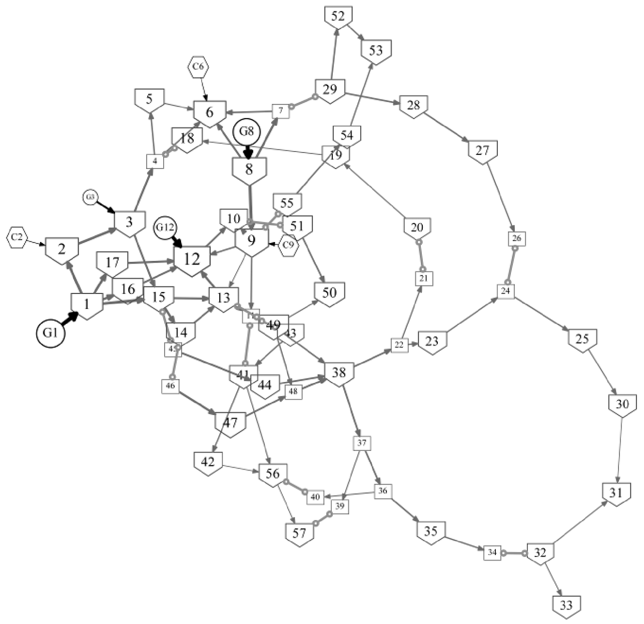

Fig. 3 *Graph representation of the IEEE 59 bus test system*

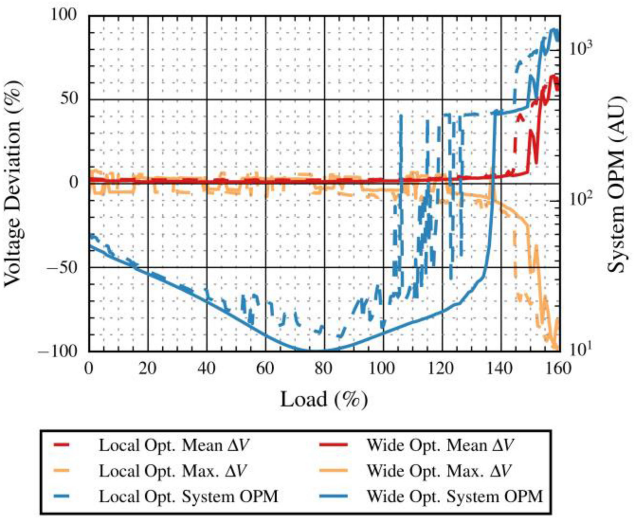

Fig. 4 *Variations in mean and max. voltage deviation, along with OPM. Load is varied under local and wide-area control, IEEE 59 Bus System*

Voltage collapse occurred on the IEEE models at high loads, this occurred as the total reactive power demand of the networks began to tend towards infinity. In this case, voltage collapse was deferred by 4% and was largely due to a general reduction in reactive power demand across the load scheme. It is worth noting that the observed collapse occurs well outside the intended load for the model and may be a feature of the model, more than a feature of a real system. Regardless, the OPM driven wide-area optimisation method performing well in an unusual situation.

The greatest effect OPM optimisation has on this system is in optimising bus voltages without increasing transmission losses or reactive power demand. It can be observed between a load of 35 and 110% that mean bus voltage deviation is reduced from 2–4% to 1–2%. Similarly, maximum bus voltage deviation is reduced from 5–6% to 2–4% with wide-area optimisation. Typically lowering voltages would result in increased transmission losses. In this case, transmission losses were unchanged as a reduced reactive power demand compensated for the lower voltages.

4.2 Optimisation of IEEE 57 Bus model

Displayed in Fig. 3 is a graphical (or network) representation of the IEEE 57 Bus model. This type of diagram better demonstrates the features of this power system; particularly, the centralised power generation and load centres that feed power out to the remote loads on the rings. On this power system, most voltage infringements originate from Bus 31 in the bottom right of the diagram, which is a particularly remote load bus. In Fig. 3, line lengths are scaled by their impedance, the thickness by the magnitude of power flow, the arrows indicate the direction of power flow, the sizes of the nodes are determined by their load/generation, circles are generators, squares are substations and the inverted houses are loads.

The most significant benefit from wide-area control of this system is the delay in voltage infringements by 32%, from 106 to 138%. It is evident from Fig. 4 that the voltage infringements that occur on the locally optimised case are caused by oversight, rather than inability, as viable system states are applied between a load of 106 and 126.5%. The infringements occur at Bus 31 due to the under voltage conditions and are alleviated by the OLTC transformer that supplies Bus 32. Wide-area optimisation strikes a balance between high voltages on the supply side and low voltages on the demand side. By maintaining this balance wide-area control prevents voltage violations by a further 11.5% load increase compared with local control. This could be an ideal application for a technology such as SuperTAPP [11] control.

A voltage collapse, such as that on the 30 Bus model, occurred as the reactive power draw tended to infinity. This collapse was delayed by 7%, from 145 to 152%. As with the 30 Bus Model, the deferment of the voltage collapse on the model was largely a result of reduced reactive power consumption.

Between a load of 0 and 110%, the wide-area and locally controlled cases differed little. The OPM indicates slight advantages that arise from a 1 to 3% reduction in transmission losses, a slight improvement in power factor, mean voltage deviation reduced from 2 to 1% and max deviation from 5–6% to 3–4%.

5 Discussion

The OPM was originally developed as a tool to rapidly test and compare system states. To this end, the simplest and safest real-world application of the metric is for control room situational awareness, such as in a traffic light system. The OPM can raise the attention of undesirable conditions developing on obscure parts of the power system. The cost factors that are used to generate the OPM can prove informative in relation to undesirable circumstances, such as transmission losses, individual voltage exceptions or general voltage exceptions. If engineers wish to tune the optimisation metrics then they can be multiplied by a scaling factor, and the protection factors changed by adjusting the values in Table 2. The OPM and cost factors can readily be communicated over SCADA, given their small size.

A logical real-time application of the OPM is in assessing the desirability of certain control applications; e.g. switching in or out a line to relieve congestion or generator dispatch. The OPM can also be used for off-line sensitivity analysis in relation to the effects of asset operation on system health. Similarly, the OPM can be used to test the desirability of current control settings on assets.

It was noted that the OPM of the local and the wide-area optimised models often converged at a load of 100%. This results from the voltage set points for the OLTC transformers being set for optimal load flow at standard load. This validates the wide-area optimised system state at this load and demonstrates the potential of this method for finding optimal voltage set points for large or dynamic systems.

Three potential difficulties with this approach are the problem of local minima, over the use of assets and potential noise in the OPM. Local minima can interfere with the gradient descent technique applied. Gradient descent techniques are vulnerable to getting stuck in local minima. In this investigation, various strategies were employed to look for and avoid local minima, but they did not appear on any complete systems. In this investigation, OLTC transformers were optimised, however, these assets wear out with use and are costly to replace. While wide-area optimisation did not significantly increase OLTC use, the gradient decent technique would. Continuous variables, such as reactive dispatch from generators, may make better use of this technique. Finally, if an asset is to use the OPM as an optimisation metric, then the effect it has on the OPM must be larger than the random fluctuations in the OPM. On a large system, a small asset operation may not register; though local area OPM applications have been investigated.

6 Conclusion

This study presents a method of reducing a vast amount of PMU data, from across a power system, into a single metric. Engineers can use the raw OPM for situational awareness and feedback on network changes; while intelligent embedded devices [2] can use it for real-time control. In this investigation, the wide-area control strategy found novel solutions for improving network conditions in circumstances it was not designed for.

On the IEEE 30 Bus Test System, small deferments of 2.5 and 7% were achieved in delaying line thermal infringements and voltage exceptions, respectively. On the IEEE 57 Bus System voltage violations were delayed by 32%. Local control of this system was unaware of exceptions on the distribution system, while wide-area control balanced high transmission and low-distribution voltages.

Wide-area control consistently reduced reactive power demand, which was beneficial for optimising system state, but also delayed voltage collapse on the models by between 4 and 7%. Using the OPM also tended to reduce mean bus voltage deviation to <2%, typically lowering it, while maintaining or reducing transmission losses.

7 Acknowledgments

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